phase. This will require six more slots to be cut out, intermediate between the original six. The twelve slots may all be of half the size of the six in the original design, since (for equal total output) half the current will be carried by the coils of one phase, and half by the coils of the other phase. So we arrive at the form of Fig. 82. If we suppose the circuits of each phase to work at the same voltage as before, we shall still have 120 conductors in each slot, but the conductors themselves will be thinner. From this it is a simple transition to Fig. 83, in which the coils of the two sets are rearranged so as not to overlap, but thereby are narrowed, having a fractional pitch, and indeed making narrower field-poles advisable. So far we have one tooth per phase per pole, but it is a simple transition to Fig. 84, in which, while the coils overlap, the slots are doubled in number and reduced to half the size, so that each slot now carries only 60 conductors. There are now two teeth per phase per pole. From this, again, it is an easy transition to Fig. 85, in which the number of slots has again been doubled, and the 60 windings of each loop have been divided into two parts of 30 each in series, so as to be better distributed over the periphery. This plan is an excellent one, and is largely adopted in the stationary armatures of polyphase generators (see for example, Figs. 101 and 163), and for the stators of polyphase motors (see Figs. 170 and 204). This spreading-out of the conductors will, however, slightly reduce the coefficient k, say from the original 2·8 to 2·3.

Returning to the hemi-tropic modification of Fig. 80, we see that it lends itself readily to two-phase grouping. If we take two such sets of 3 coils as are there shown, and displace one set through half the pole-pitch, we get the form shown in Fig. 86 with 12 slots. Pushing the principle logically to conclusions we may derive Fig. 87 from Fig. 81 ; and here, by displacing the second set of coils through a distance equal to $1\frac{1}{2}$ (instead of $\frac{1}{2}$) times the pole-pitch, we obtain a case without overlap. Here there are eight equidistant slots. Fig. 88 is a further development, using 24 slots of which 16 only are occupied with coils. These constructions are suitable only for machines having an odd number of pairs of poles, 6-pole,

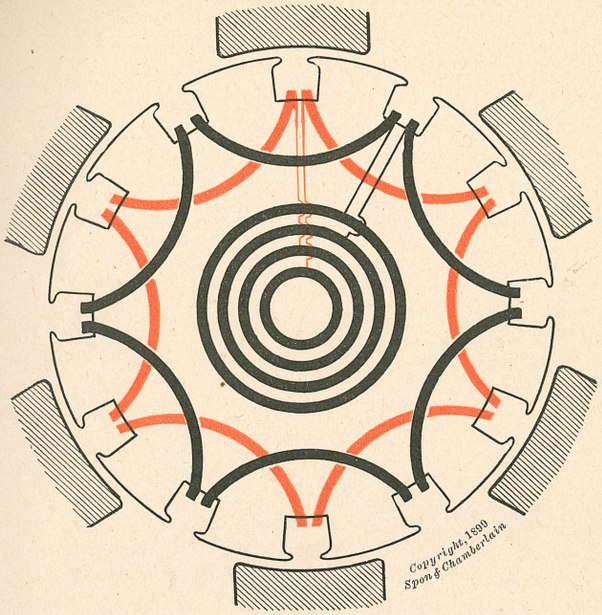


Fig: 82.

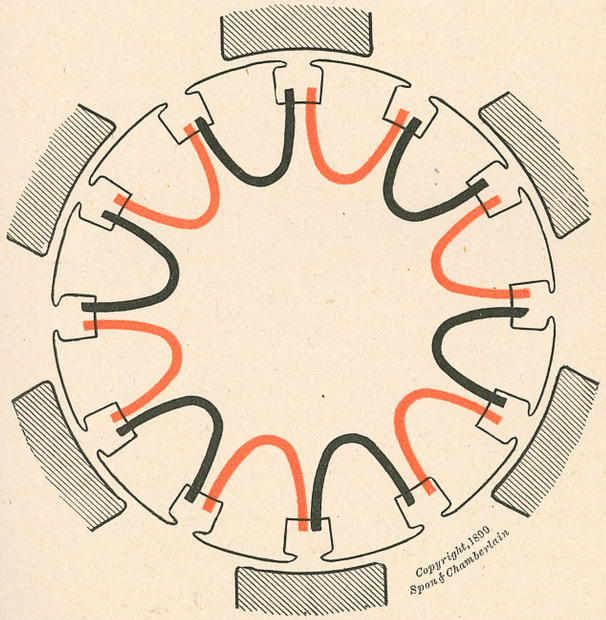
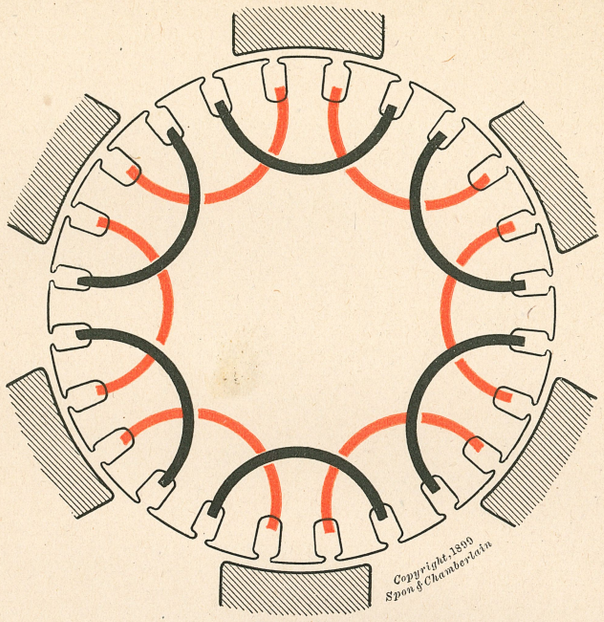


Fig: 83.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Spon & Chamberlain

Fig: 84.

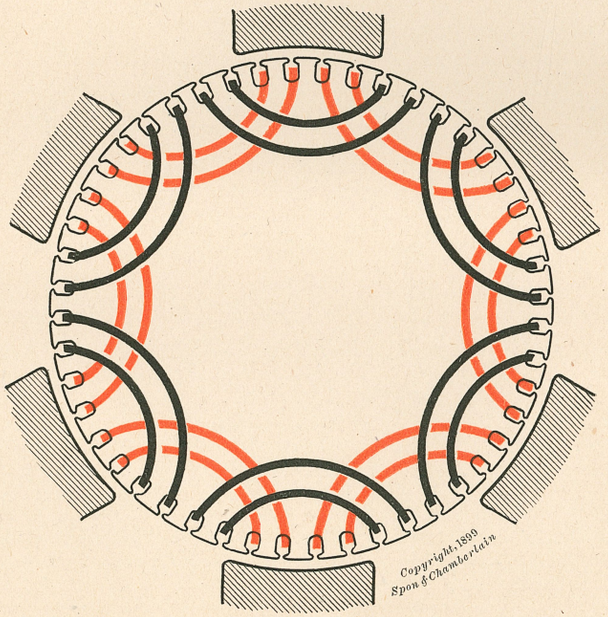
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Fig: 85.

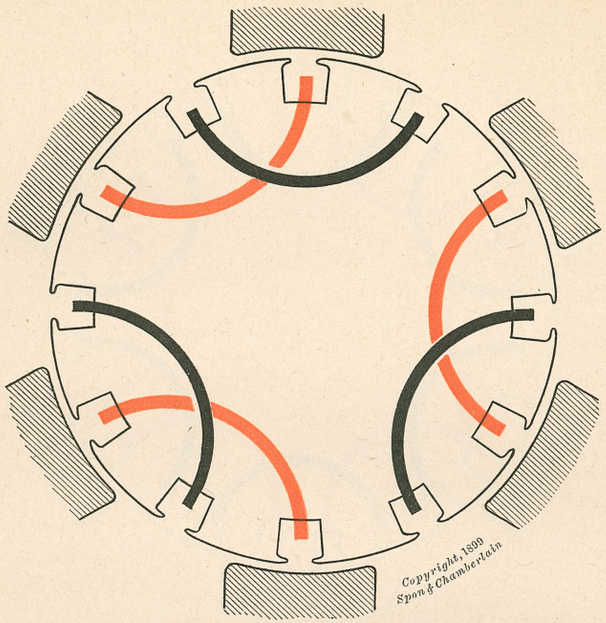

Fig: 86.

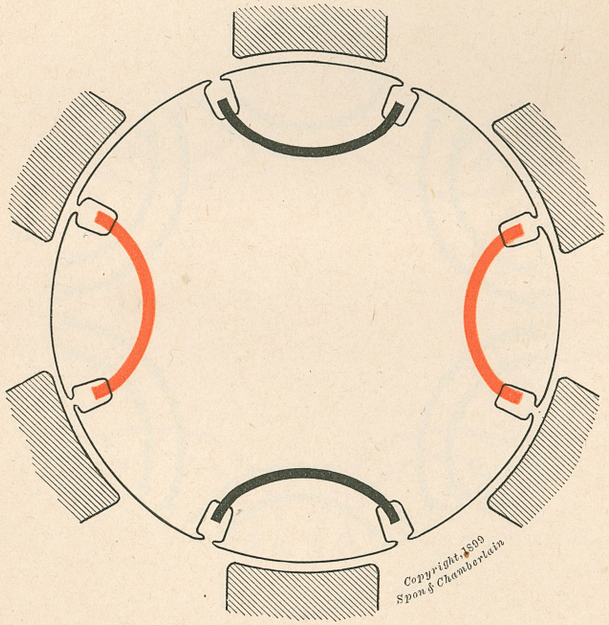

Fig: 87.

10-pole, 14-pole, etc., and cannot be used with 4-pole, 8-pole, 12-pole, etc., machines. In all cases it will be seen, that the distance between the central lines of two successive coils of the same phase-set is either equal to the pole-pitch, or to the pole-pitch multiplied by two or by three, and that the distance between the central lines of the coils of one phase-set and those of the other phase-set, is equal to half the pole-pitch or to $1\frac{1}{2}$ times the pole-pitch.

In all cases the lines shown as coils or loops may be supposed to consist of any desired number of individual coils in series, according to the voltage required.

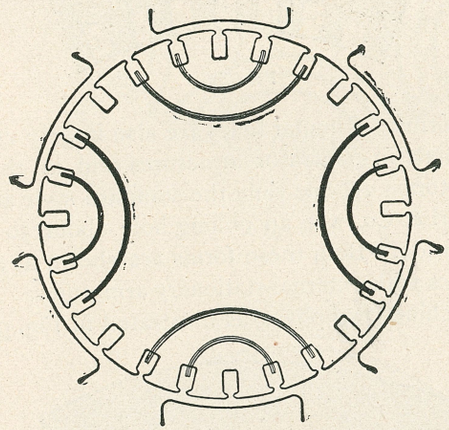

FIG. 88.

It was remarked above that the more the windings are concentrated into few slots the more do armature reactions perturb the field. For example, Figs. 86 and 85 above may be practically alike in the electromotive-force they generate if the total number of windings is alike, but Fig. 85 will perturb the field less, and either of them will perturb the field less than the single-phase winding, Fig. 78, that gives the same total current at the same voltage; for the simple reason that now that the output is separated into two separate phases, when one-half of the current is at its maximum and producing perturbations, the other is out of its maximum: the perturbing

reactions are only half as intense, and they are distributed nearly uniformly in time.

Slotted core-disks, therefore, become an essential feature of polyphase construction. Mr. C. E. L. Brown introduced the practice of embedding the conductors in holes pierced through the core-disks. Slots and holes of various shapes are in use. Fig. 89 shows a form used on both sides of the Atlantic. Fig. 90, with pierced holes, is more characteristic

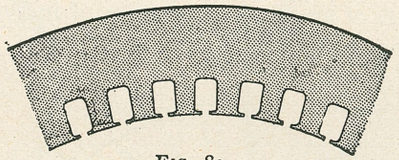

FIG. 89.

of the Swiss firms. Circular holes are also largely used in certain cases, both in generator armatures and in the rotor of induction motors. At one time the standard style adopted by Brown, Boveri & Co., was an oblong hole about 50 mm. long and 20 mm. wide. Both these forms are shown as applied to large machines with external stationary armatures. A portion of such a machine (two-phase) is illustrated in Fig. 91, having

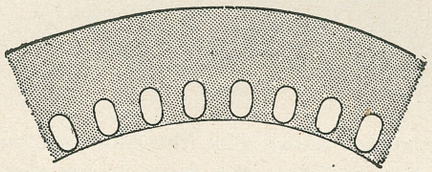

FIG. 90.

the windings distributed in two slots per phase per pole, and arranged on Brown's plan in two ranges.

In order still further to spread the conductors, the plan of distributing them in separate slots may be carried further. For example, in the six-pole case under consideration, in which each phase consists of 720 conductors in series, they might be distributed in 72 slots (i.e. 36 slots per phase), with 20 conductors in each slot, or 1440 conductors in total. Fig. 92 shows a complete diagram for this particular case; each

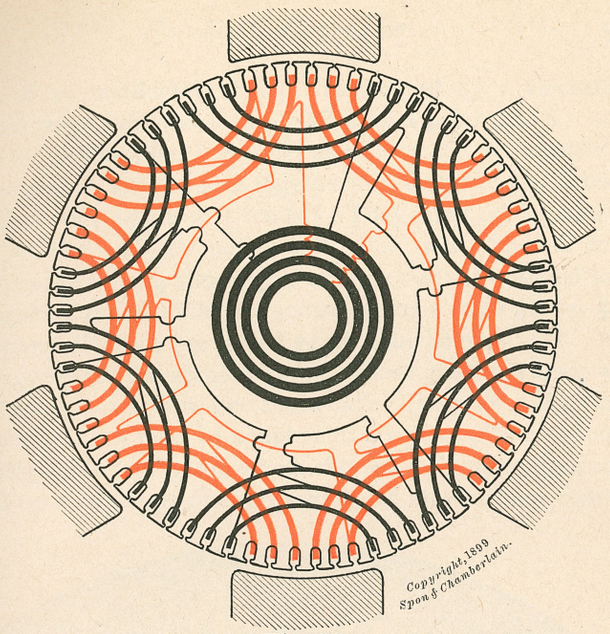

Fig: 92.

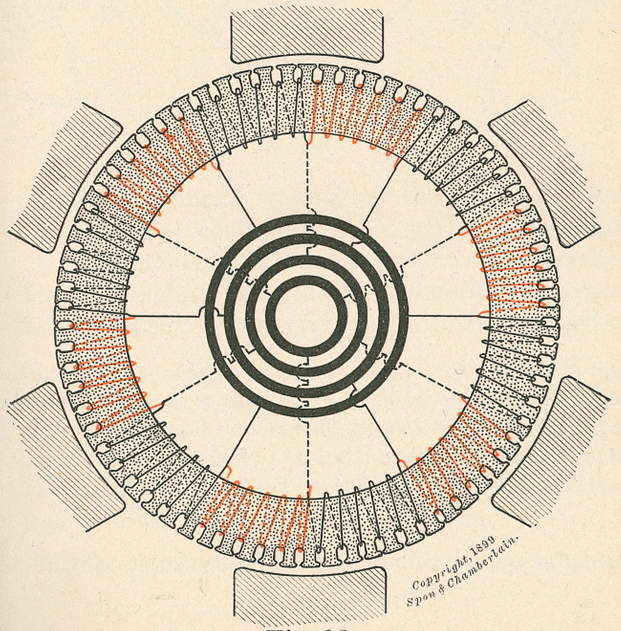

Fig: 93.

the twelve segments to be disjoined from one another, and then reconnected into two separate series, according to phase, as in Fig. 94. The two sets of segments so united are marked respectively A and B. The electromotive-force of each circuit will now be six times as great as when the segments were in parallel. (Or, in the numerical example chosen = 2340 volts. This falls behind the 3000 volts g ven by the same number of

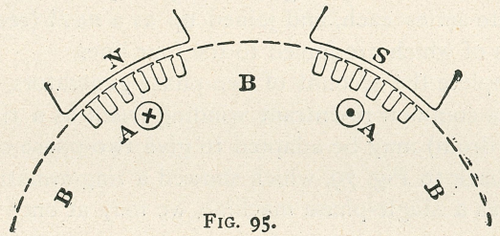

FIG. 95.

wires arranged in a concentrated winding, p. 84 above, owing to the lower coefficient for the distributive grouping.)

We can now readily see the relation between the case presented by Fig. 94, which was derived from the purely distributive ring-winding, and those presented by the figures successively derived from the concentrated winding. Consider two successive parts of either of the circuits—for instance,

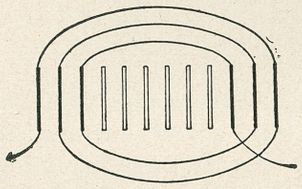

FIG. 96.

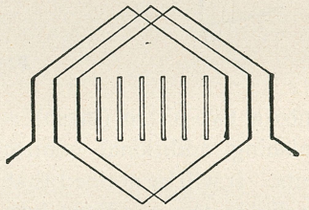

FIG. 97.

two pieces of the A circuit—as in Fig. 95. When one of these is passing a N-pole the other is passing a S-pole, so that the induced currents in them will be oppositely directed. It will therefore make no difference, electrically, to those that are grouped in series whether they are joined up as in Fig. 96 or as in Fig. 97. Now Fig. 96 is the form of connection derived from the concentrated winding, while Fig. 97 is simply a piece

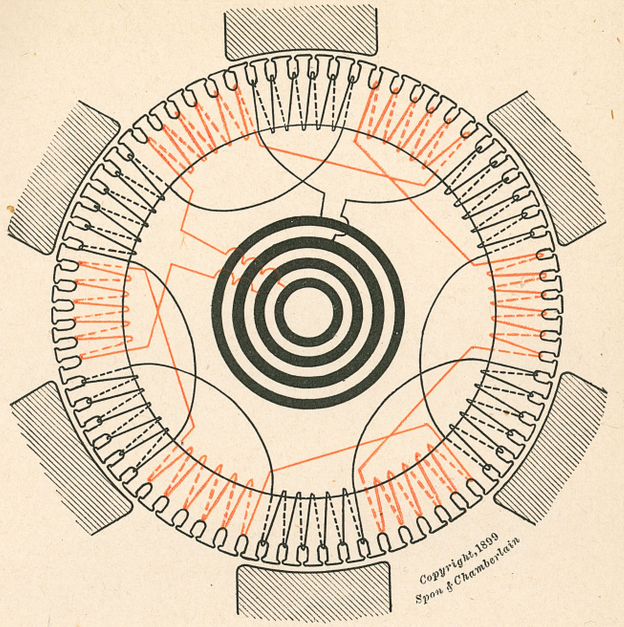

Fig: 94.

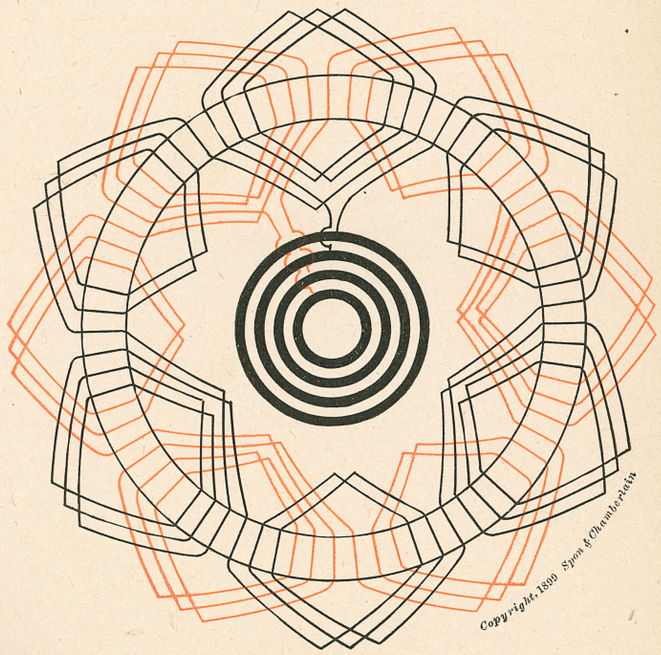

Fig: 98.

Fig: 99.

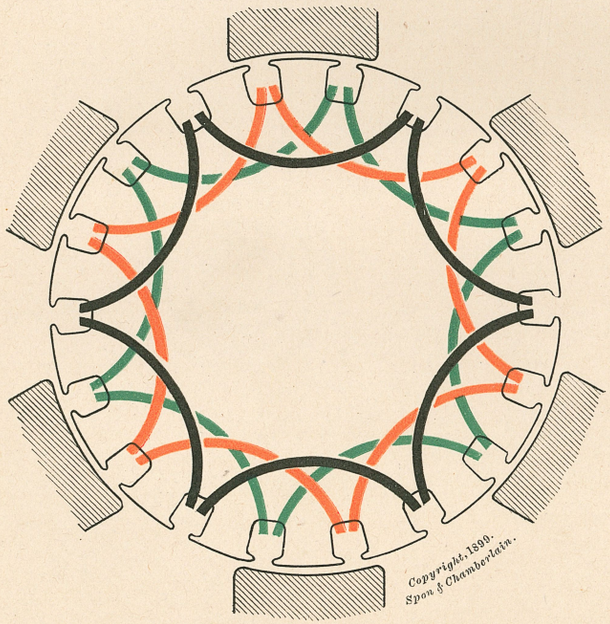

Fig: 102.

of a lap-winding (page 5), which is the equivalent of a ring-winding. In fact, Fig. 98, which is a lap-winding, with seventy-two slots, coiled like Fig. 97, is electrically identical with Fig. 94, which is ring-wound as described. Fig. 99 is an equivalent wave-winding, with this difference only, that the seventy-two bars or conductors are supposed to be set two in a slot, there being thirty-six slots instead of seventy-two.

Windings such as Figs. 84 and 85, with two sets of coils, were originally devised by Mr. C. E. L. Brown, and have been widely adopted. To carry them out mechanically, the two sets are arranged to be bent into two different planes, where

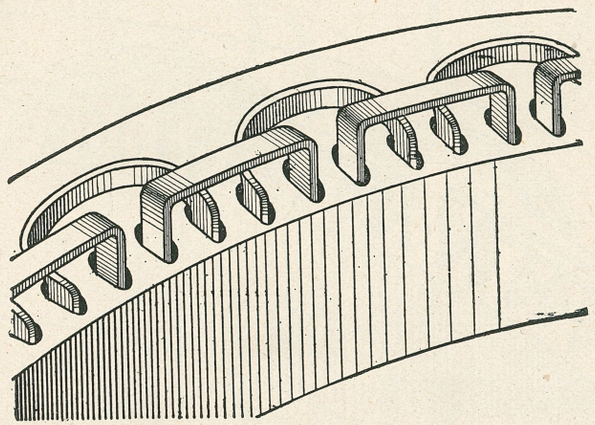

FIG. 100.

they stand well apart from one another. These sketches, Figs. 100 and 101, which show how Brown's method is applied to stationary external armatures, should be compared with Figs. 127 and 163, which depict actual machines wound in this manner.

Application to Three-phase Designs.—It is equally easy to apply the same general principles to three-phase designs. Let us return to the single-phase unitooth armature of Fig. 78. If three such windings are superposed and spaced out symmetrically, we shall require the core-disks to be made with 18 slots, or 6 slots for each of the three phases, as in Fig. 102.

For equal total output, these slots need only be made about one-third as large as in the single-phase case, since (other things being equal) each of the three circuits will have to carry only one-third of the total current. Each slot will carry 120 conductors as before. A simple transition, substituting hemitropic windings, leads to Fig. 103 and Fig. 104, the latter of which is preferable because of its simpler overlapping. In fact, though three-phase it could be wound in two ranges in two planes, as just described above. By duplicating the number of slots we arrive at the more distributive arrangement of Fig. 105. In Fig. 106 we have another rearrangement in

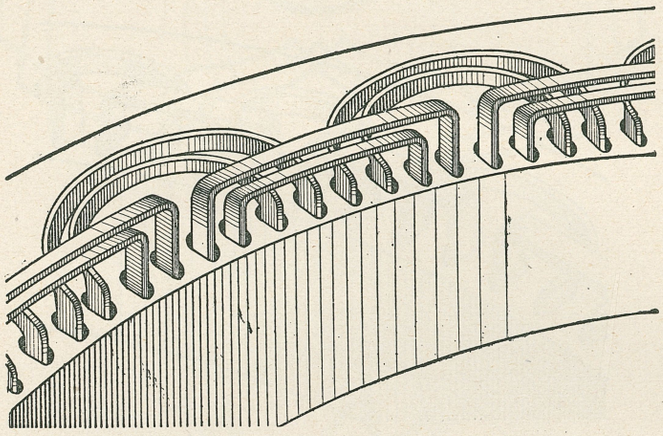

FIG. 101.

which only nine slots are used, each carrying 240 conductors. Fig. 107, in which the concentration of the grouping has been carried to an extreme, has only six slots. It is applicable only to a 4-pole machine, or by reduplication to an 8-pole or 12-pole machine; but is inapplicable to 6-pole, 10-pole or 14-pole machines. Fig. 108 shows an electrically identical winding, with the coils distributed in 12 slots in core with 18 slots.

It will be noted that in all these three-phase cases the angular distance from the centre part of one coil to the centre part of the next coil of the same phase, is equal either to the pole-pitch or to twice or three times the pole-pitch, while

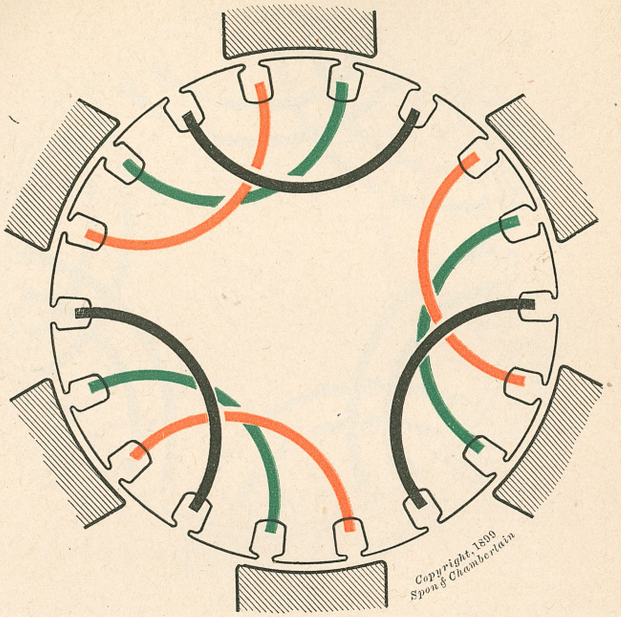

Fig: 103.

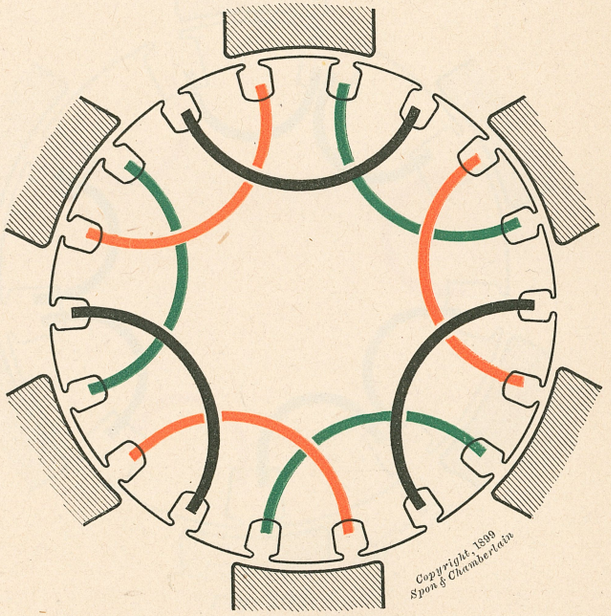

Fig: 104.

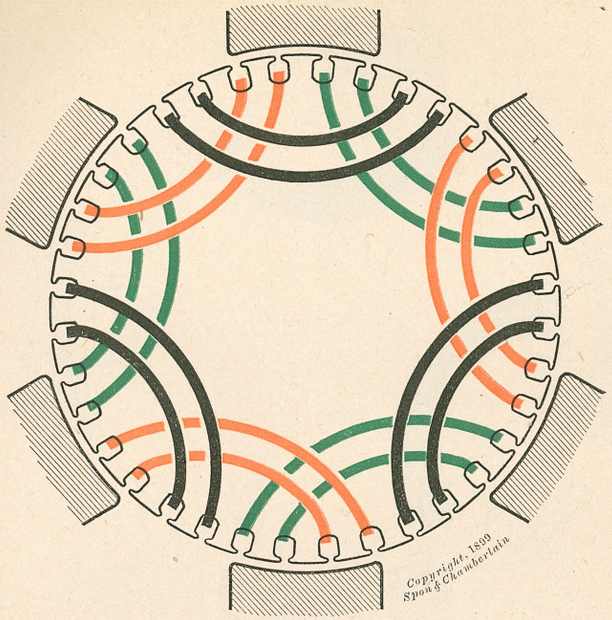

Fig: 105.

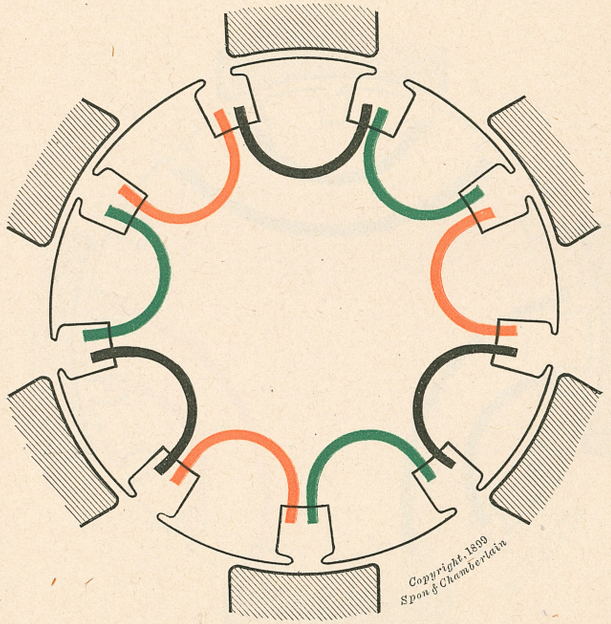

Fig: 106.

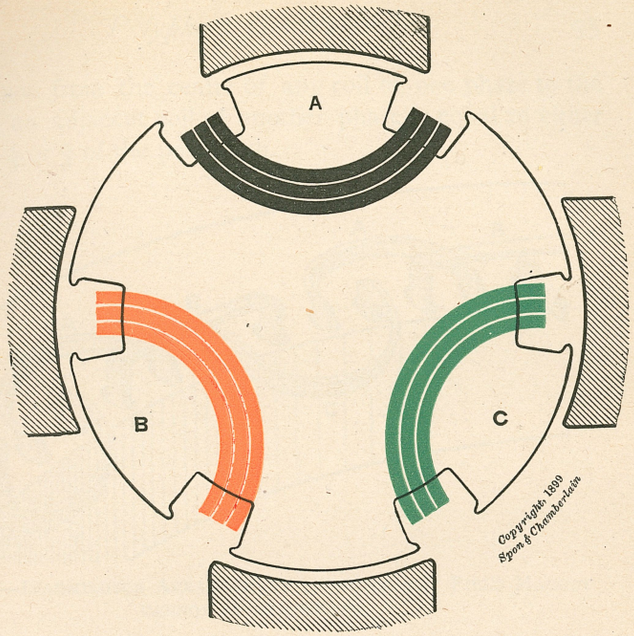

Fig: 107.

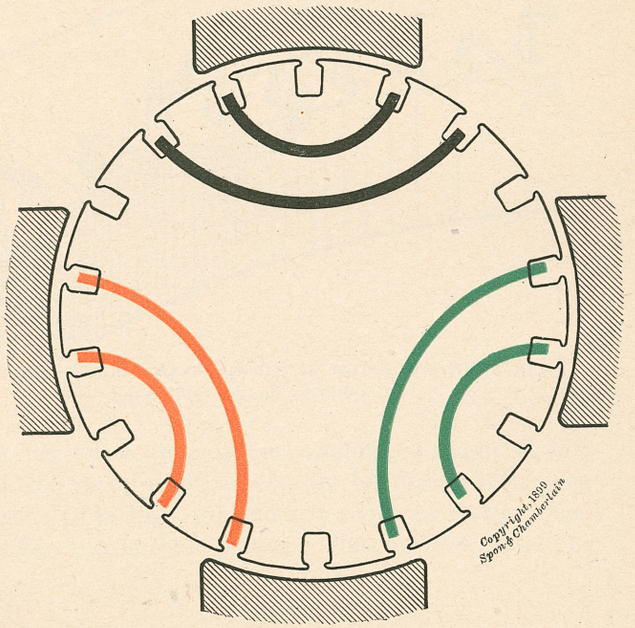

Fig: 108.

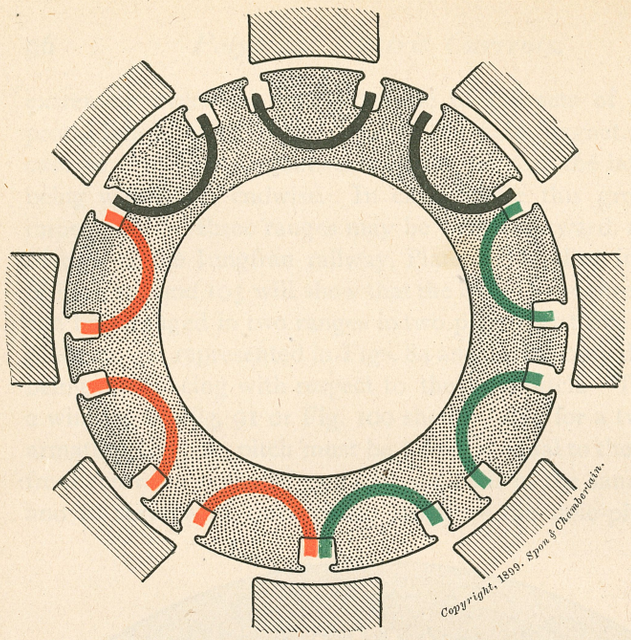

Fig: 113.

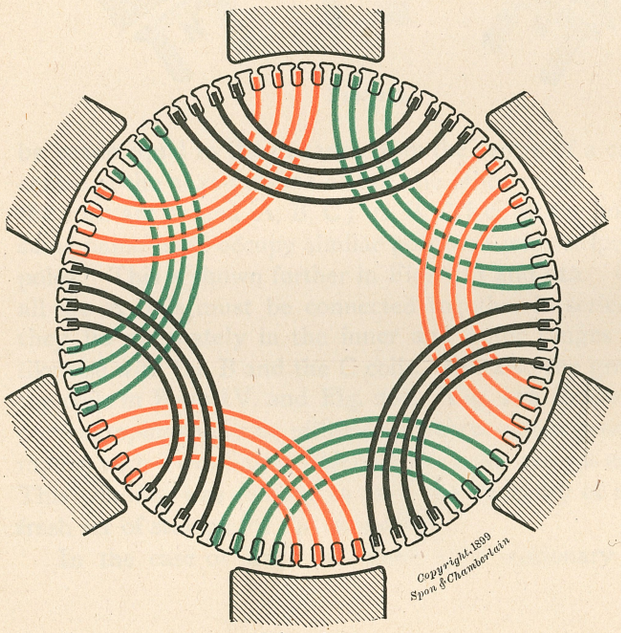

Fig: 114.

armatures, this particular arrangement of three-phase coils in two ranges has one disadvantage. The coils overlap one another at the ends, so that at no part of the whole periphery can the armature be divided—for example, to enable the upper half to be lifted off the machine. In this case the adoption of the hemi-tropic mode of winding enables a disposition in three planes to be adopted, as shown in Fig. 110. The armature might be mechanically divided along the dotted line, without requiring the unwinding of any coil, but merely the disjoining of connexions between coils of the same range.

There is yet another way of grouping coils for three-phase action, in which the number of coils is either one greater or one less than the number of poles: for example, 9 coils (i.e. 3 of

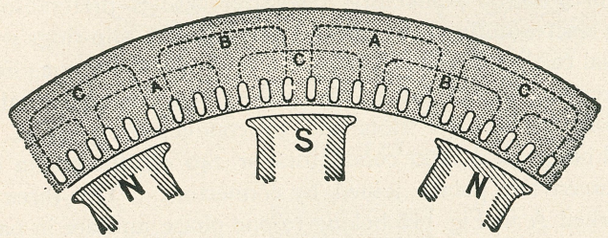

FIG. 112.

each of three phases) in an 8-pole or a 10-pole field. The coils of one phase are then adjacent to one another. Fig. 113 shows a way of carrying this out. The formula for this winding is

$$2p \pm 1 = 3a \text{ (for three-phase)};$$

where p is the number of pole-pairs and a the number of coils per phase. The coils are of fractional pitch, and those of one phase are spaced apart or crowded together, according as whether the number of coils is chosen greater or less than the number of poles.

What has been said above about the distributing of the coils over more numerous slots is applicable, of course, to three-phase windings. Fig. 114 shows the same 6-pole case modified so as to have 72 slots, that is 24 slots per phase, and as each phase has (in the numerical example) chosen 720 conductors,

there will be 30 conductors per slot. It is simply Fig. 105 with the bunches of conductors subdivided.

Fig. 115, which is electrically identical with the last, shows how, for the distributed bunches of looped coils, a lap-winding may be substituted. This last, which is suitable for a bar-armature, is shown connected up, as a Y, with a common junction J and three slip-rings.

In the case of two-phase armatures, as also in the case of three-phase, a re-entrant distributive winding, such as a ring or a re-entrant lap-drum, may be adapted as a three-phase armature by connecting down by radial connectors to three slip-rings; the connectors being jointed in to the winding at successive points equidistant by either $\frac{1}{3}$ or $\frac{2}{3}$ of the pole-pitch. In the case of a 6-pole machine there will, therefore, be either 18 or 9 radial connectors (the latter case is preferable), and the electromotive-force between two of the slip-rings will be equal to that developed in so much of the winding as lies between any two adjacent connectors. In the numerical case before us, with 72 slots and 30 conductors per slot, there will be in total 2160 conductors, or 240 conductors, in series between the points joined by connectors. The three parts marked A in Fig. 116 belong to one phase, and are in parallel with one another; so also the three parts marked B in the second phase, and the three parts marked C in the third phase. The grouping is, of course, of the mesh or Δ kind.

If instead of making the winding re-entrant the 12 segments were disconnected, and then reunited so that all the A segments were joined in series for one phase, all the B segments for a second phase, all the C segments for the third phase, we should arrive at an arrangement in which, as in some of the preceding cases, such as Fig. 114, there are three independent circuits each of 720 conductors in series.

An analogous mode of adapting to polyphase purposes a re-entrant wave-winding[1] is possible. All that is requisite is to ascertain three points symmetrically equidistant along the

[1] It is so called in contradistinction to lap-winding, and is also sometimes called a multipolar series winding. See the author's treatise on *Dynamo-Electric Machinery*.

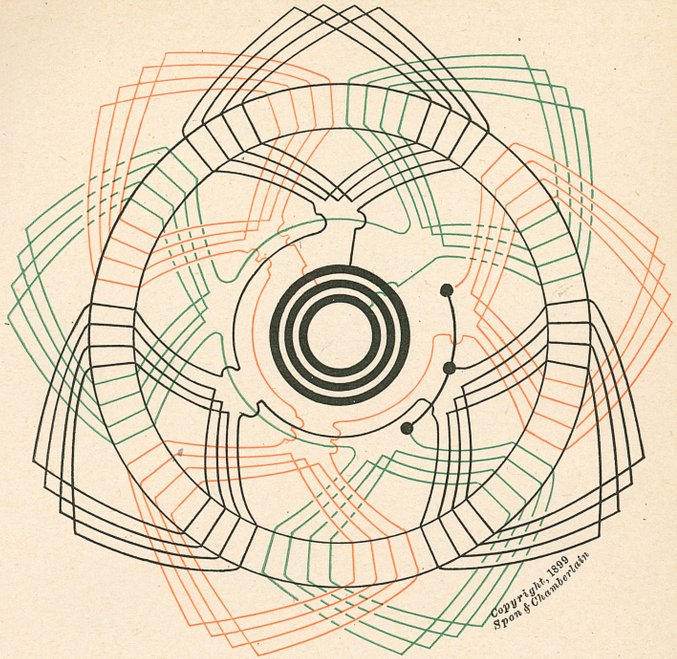

Fig: 115.

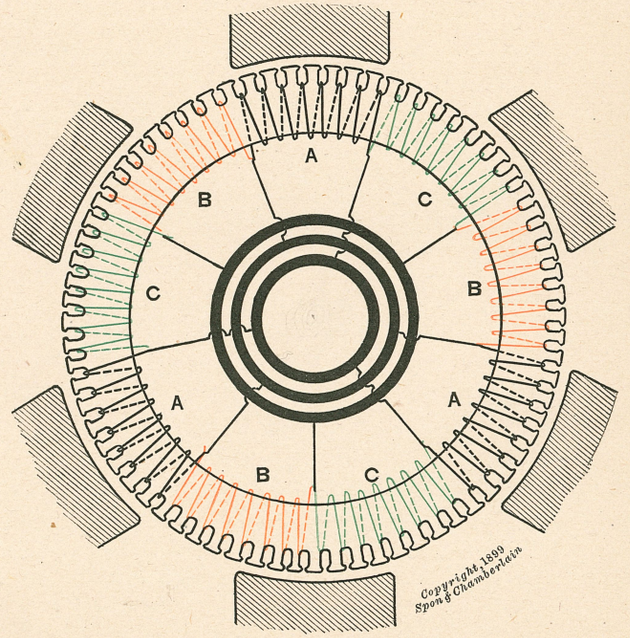

Fig: 116.

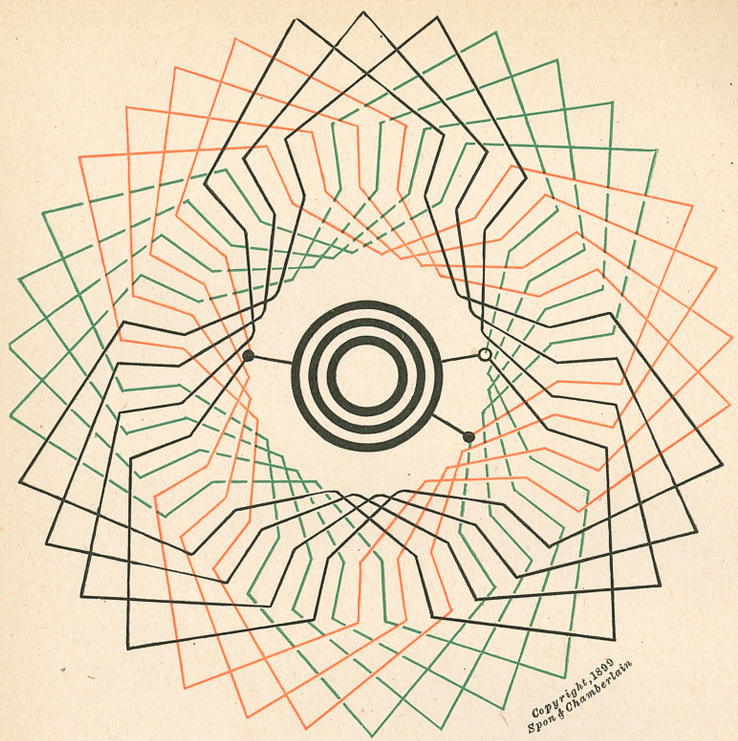

Fig: 117.

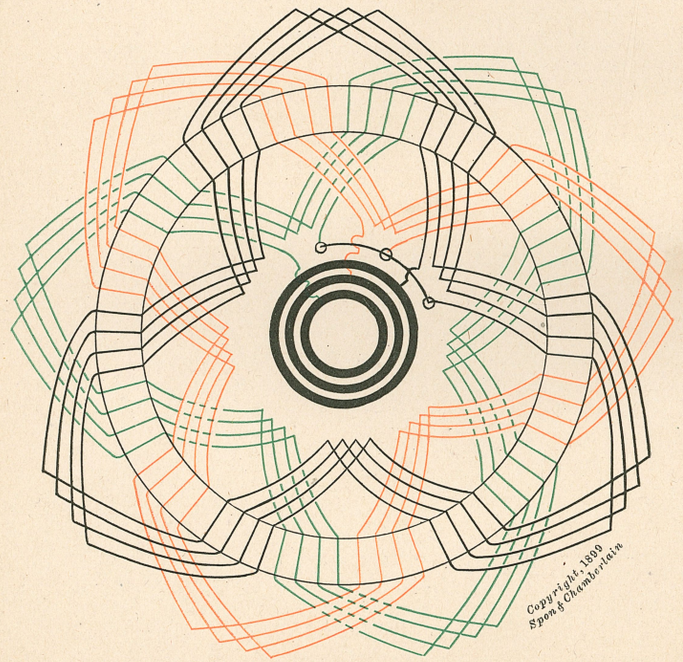

Fig: 118.

closed winding, and join them down by three connectors to the three slip-rings: for example, if an 8-pole armature be wound with 402 conductors (which gives a singly re-entrant wave-winding), it can be used as a three-phase machine by connectors joined in at Nos. 1, 135 and 269 of the conductors. In the same way a two-phase machine can be made by joining down at four equidistant points to the four slip-rings: for example, in a 6-pole machine with 488 conductors (which gives a singly re-entrant wave-winding), the connecting points would be at conductors Nos. 1, 123, 245 and 367. Fig. 117 shows a 6-pole re-entrant wave-winding with 68 conductors, joined up as a Δ three-phase armature. The Y connection cannot be made if the winding is re-entrant. Fig. 118 shows a Y-connected winding, with common junction J. This is a 6-pole wave-winding with 72 conductors. It is, save for the Y-connection, electrically equivalent to the lap-winding, Fig. 115.

Amid the multitude of possible cases the question naturally arises, which modes of winding are preferable? In cases where polyphase generators are employed for long-distance transmission, the voltage must be high, frequently from 3000 to 5000 volts, occasionally 10,000 to 15,000 volts. The Chèvres two-phase machines work at 2500 volts, the Paderno three-phase generators at 15,000 volts (see Chapter XVII). In such cases numerous conductors and very high insulation are necessities; and the conductors consist of wire actually wound in many turns. On the other hand, for driving motors in factories at a short distance from the generator, the voltage need not exceed say 200 or 300 volts, and in such cases copper bar conductors comparatively few in number will suffice, but they must be considerably more numerous than the poles. Now, in the wire windings good insulation is best secured by bunching the many turns of insulated wire in a few groups, which groups are then carried through a few large slots very highly insulated with micanite tubes. The most frequently adopted case for such extra high voltage generators is one slot per phase per pole. That is, in a 6-pole machine, 12 slots for a two-phase winding (Figs. 82 and 86), or 18 slots for a three-phase winding (Figs. 102 and 104).